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Indirect transitions at a free carrier front in a silicon slow light waveguide

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Abstract: A signal wave interacting with a free carrier front in a slow light waveguide experiences indirect transitions leading to transmission or reflection from the front. Theory and experimental results are presented.

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1. Introduction

The process of an optical signal undergoing a transition between two modes of a photonic structure is referred to as a photonic transition. Photonic transitions can be direct, if the optical signal experiences a shift in frequency but not in wave vector, or indirect, if both frequency and wave vector of the signal are changed [1,2,3]. The indirect photonic transitions between modes that belong to different photonic bands are called indirect *inter-band* transitions [4,5], while transitions to the same band are called indirect *intra-band* transitions [6]. The required fast change of refractive index is achieved by generating free carriers in silicon, which leads to a refractive index change via the carrier plasma dispersion effect.

We have shown that signal interaction with a front in a photonic crystal waveguide can induce an indirect transition [4,6]. In this case the frequency and wave number of the signal changes inside the front, where ratio of the frequency change to the wavenumber change stays constant and is equal to the front velocity. Thus the new state of the signal lies on the line, which we call a phase continuity line, as it can be derived from the signal phase continuity relation at the front. We show, that with the flexibility in dispersion designs of PhC waveguides [7,8], a variety of indirect transitions can be envisaged. We experimentally demonstrate two examples [4,6] and discuss possible applications [9].

2. Inter-band indirect photonic transition

To implement indirect transitions, we employed single line defect PhC waveguide fabricated on a Silicon-on-Insulator substrate with slab height of 220 nm. The lattice constant of the PhC is 404 nm and the air-hole diameter is 230 nm [4]. Further, the first row of holes directly adjacent to the waveguide has been shifted 50 nm away from the waveguide center [8]. Figure 1(a) shows the measured group index of the TE-mode of the slow light PhC waveguide. In order to induce an inter-band indirect transition, we chose the wavelengths and group indices of pump pulse and signal wave as indicated by orange and red dots, respectively. This means that the pump pulse is faster than the signal wave, and therefore will overtake it. The basic concept to induce this transition is schematically shown in Fig. 1(b). At the input of the structure, the signal wave travels in a waveguide with silicon refractive index of n_{si}, and is represented by a point (ω_1, k_1). The final state of the signal (ω_2, k_2) after interaction with the moving front is determined by the crossing point of the phase continuity line and the upper dashed dispersion curve. This means that the signal pulse is overtaken by the front and travels in a waveguide with silicon refractive index of $n_{si} + \Delta n_{FC}$ with higher frequency. Figure 1(c) shows a schematic illustration of this process at two different times.

3. Intra-band indirect photonic transition

Now, we are interested in the particular situation where the signal wave ahead of a front cannot find states on the band of the switched PhC behind the front. This can happen when the phase continuity line does not cut through the band of the perturbed PhC. Thus, the state of the signal wave, after interacting with the moving front, must remain in the initial band which means that an intra-band transition takes place. This intra-band transition manifests itself as a forward reflection from the front. Figure 2(a) shows the measured group index of the TE-mode of the engineered

PhC waveguide. Figure 2(b) presents a schematic representation of the intra-band indirect photonic transition, which can be obtained by setting the signal wave at a frequency close to the knee of the solid line. The knee of the solid line represents point A in Fig. 2(a), while the orange dot represents point C. In such configuration, the signal wave is initially propagating slower than the approaching pump pulse. The final state of the signal $(\omega_2,\ k_2)$ after interaction with the front is determined graphically from the crossing point of the phase continuity line and the solid band. Fig. 2(c) shows a schematic illustration of intra-band transition process. A signal wave escapes from the moving front in the forward direction.

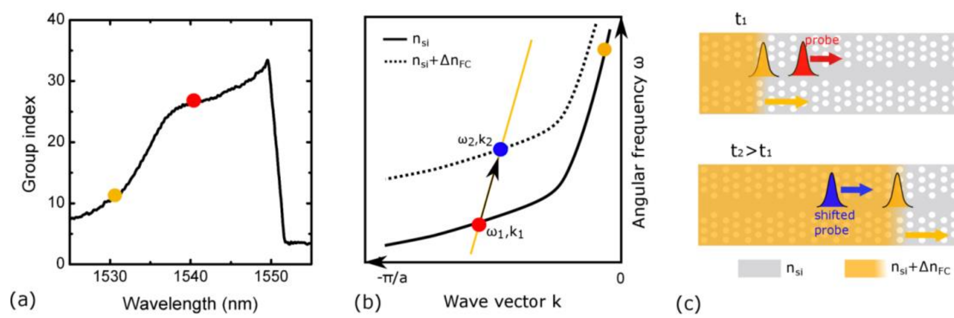

Figure 1: (a) Measured group index of the engineered and fabricated slow light silicon PhC waveguide, where input signal wave (red dot) and pump pulse (orange dot) are shown. (b) Schematic representation of an inter-band indirect photonic transition. The solid curve represents the dispersion band of waveguide mode in the ground state (with refractive index n_{si}), while the dashed curve indicates the switched state with refractive index $n_{si} + \Delta n_{FC}$. The orange line represents the phase continuity line with a slope equal to the group velocity of the pump pulse. Blue dot indicates the expected output wavelength of the shifted signal wave after inter-band transition took place. (c) Schematic of the experiment. A pump pulse generates free carriers in the silicon by TPA and, consequently, induces a change of refractive index which propagates with the velocity of the pump pulse. The region with the orange color gradient corresponds to the rising edge of the front. The orange arrow indicates the velocity of the pump pulse, while red and blue arrows indicate the velocities of the signal at different times.

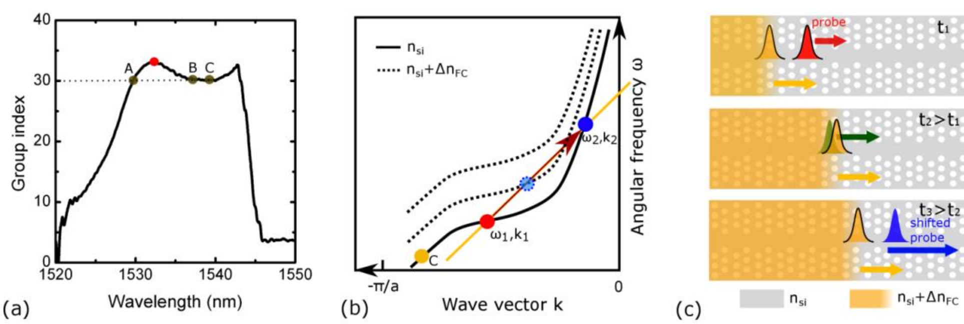

Figure 2: (a) Measured group index of the engineered slow light silicon PhC waveguide. Here, the dispersion relation shows equal group velocities at three different frequencies A, B and C. (b) Schematic representation of an intra-band indirect photonic transition, obtained by setting the signal wave at a frequency close to the knee of the solid line and the pump pulses corresponding to point C in (a). The inter-band and intra-band photonic transitions of the input signal caused by insufficient (dashed blue dot) and by sufficient (solid blue dots) values of Δn, respectively. (c) Schematic of the experiment. The orange arrow indicates the velocity of the pump pulse, while red, green, and blue arrows indicate the velocities of the signal at different times, respectively.

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